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A formula for Tignol's constant

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Abstract

Let (K, v) be a Henselian valued field and (L, w) be a finite separable extension of (K, v). In 2004, it was proved that the set $A_{L/K}$ defined by $A_{L/K} = \{v(\mathrm{Tr}_{L/K}(\alpha)) - w(\alpha) \mid \alpha \in L, \alpha \neq 0\}$ has a minimum element if and only if $[L : K] = ef$ where e, f are the ramification index and the residual degree of w/v, i.e., $(L, w)/(K, v)$ is defectless. The constant $\min A_{L/K}$ was first introduced by Tignol and is referred to as Tignol's constant. In 2005, K. Ota and Khanduja gave a formula for $\min A_{L/K}$ when $(L, w)/(K, v)$ is an extension of local fields. In this paper, we give this formula when (L, w) is any finite separable defectless extension of a Henselian valued field of arbitrary rank and thereby generalize some well-known results of Dedekind regarding "different" of extensions of algebraic number fields and ramification of prime ideals.

Keywords: Valued fields; Non-Archimedean valued fields

1. Introduction

Throughout this paper, v is a Henselian valuation of arbitrary rank of a field K and $\tilde{v}$ is the unique prolongation of v to a fixed algebraic closure $\tilde{K}$ of K. Let $(L, w) \subseteq (\tilde{K}, \tilde{v})$ be a finite extension of (K, v). The extension $(L, w)/(K, v)$ (or briefly L/K) is called defectless if $[L : K] = ef$ where e and f are the index of ramification and the residual

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degree of w/v. Since (K,v) is Henselian, for any α in L and σ in $\mathrm{Gal}(\tilde{K}/K)$, $\tilde{v}\circ\sigma(\alpha)=\tilde{v}(\alpha)$ and consequently $v(\mathrm{Tr}_{L/K}(\alpha))\geqslant w(\alpha)$; here and elsewhere Tr stands for the trace map. In 1990, Tignol proved that if $(L,w)/(K,v)$ is a finite separable defectless extension of degree equal to the characteristic of the residue field of v, then the set $A_{L/K}$ defined by

$$A_{L/K}=\{v(\mathrm{Tr}_{L/K}(\alpha))-w(\alpha)\mid \alpha\in L,\ \alpha\neq 0\}$$

has a minimum element; moreover he gave a formula to calculate $\min A_{L/K}$ in this case (see [8, Proposition 2.5], [9, Lemma 1.1]). The constant $\min A_{L/K}$ is referred to as Tignol's constant. It is also known that for a finite separable extension, Tignol's constant is zero if and only if the extension is tamely ramified (see [2]). In 2004, Khanduja and Singh [3] extended the result of Tignol besides proving its converse by showing that a finite extension (L,w) of a Henselian valued field (K,v) is defectless if and only if $A_{L/K}$ has a minimum element. They also proved that if $K\subseteq M\subseteq L$ is a tower of finite separable defectless extensions then

$$\min A_{L/K}=\min A_{L/M}+\min A_{M/K} \tag{1}$$

(see [3, Theorem 2.5]). This gives rise to the following natural question:

Question. *Can we find a simple formula for* $\min A_{L/K}$, *where* (L,w) *is any finite separable defectless extension of* (K,v)*?*

In 2005, Khanduja and Ota [4] gave a formula for Tignol's constant when (L,w) is a finite extension of a local field (K,v), i.e., K is a finite extension of the field Q_p of p-adic numbers or of $F_p((t))$. Indeed they proved that $\min A_{L/K}=\frac{d}{[L:K]}-1+\frac{1}{e}$, where e is the ramification index and P_K^d the discriminant of $(L,w)/(K,v)$, P_K being the maximal ideal of the valuation ring of v. In this paper, we give a formula for Tignol's constant when the base field is a Henselian valued field (K,v) of arbitrary rank; this formula yields "Dedekind's Theorem" regarding ramification of prime ideals in algebraic number fields and will be stated after introducing some notations.

In what follows, for a finite extension L of K contained in $\tilde{K}$, the valuation on L will be the restriction of $\tilde{v}$ and G_L, R_L, $\bar{L}$ will stand respectively for the value group, valuation ring and the residue field of this valuation. For any ξ in the valuation ring of $\tilde{v}$, $\bar{\xi}$ will denote its $\tilde{v}$-residue, i.e., the image of ξ under the canonical homomorphism from the valuation ring of $\tilde{v}$ onto its residue field. Also $e(L/K)$ will denote the ramification index, i.e., the index of the value group G_K of v in G_L. As in [1, 18.3], it can be easily seen that elements of the set

$$S_{L/K}=\{\lambda\in G_L\mid 0\leqslant\lambda<\gamma \text{ for all positive } \gamma \text{ in } G_K\} \tag{2}$$

lie in different cosets of G_L/G_K and hence $S_{L/K}$ has at most $e(L/K)$ elements. The maximum element of $S_{L/K}$ will be denoted by $\lambda_{L/K}$. We shall denote by $C_{L/K}$ the codifferent of L/K (with respect to v) defined by

$$C_{L/K} = \bigl\{\alpha \in L \mid \mathrm{Tr}_{L/K}(\alpha R_L) \subseteq R_K\bigr\}.$$

For proving the main result of this paper, it will be proved that the fractional ideal $C_{L/K}$ is principal. This result is also of independent interest. Note that in case v is a discrete valuation, then $C_{L/K}^{-1}$ is the usual different of the extension L/K (cf. [7, p. 50]).

With the above notations, we prove

Theorem 1.1. *Let v be a Henselian valuation of arbitrary rank of a field K and $\tilde{v}$ be the unique prolongation of v to the fixed algebraic closure $\tilde{K}$ of K. Let L be a finite separable defectless extension of K, then the R_L-module $C_{L/K}$ is generated by a single element and*

$$\min A_{L/K} = -\min_{\alpha\in C_{L/K}} \bigl\{\tilde{v}(\alpha)\bigr\} - \lambda_{L/K}.$$

The corollary stated below is an immediate consequence of Theorem 1.1.

Corollary 1.2. *Let v be a Henselian discrete valuation of a field K having value group $\mathbb{Z}$. Let L/K be a finite separable defectless extension with ramification index e and codifferent P_L^{-D}, P_L being the maximal ideal of the valuation ring R_L. Then*

$$\min A_{L/K} = \frac{D}{e} - \frac{e-1}{e}.$$

Keeping in mind that $\min A_{L/K} \geqslant 0$ and the result that $\min A_{L/K} = 0$ if and only if the extension L/K is tamely ramified proved in [2], the above corollary yields at once the following well-known results of Dedekind (cf. [6, Theorem 4.8, Proposition 6.2], [7, Chapter III, Propositions 10, 13, Theorem 1]).

Corollary 1.3. *Let (K, v), R_L, e and P_L be as in Corollary* 1.2 *and $\mathfrak{D}$ be the different of the extension L/K (with respect to v). Then the following hold*:

(i) *P_L^{e-1} divides $\mathfrak{D}$.*
(ii) *L/K is tamely ramified if and only if the exact power of P_L dividing $\mathfrak{D}$ is $e-1$.*
(iii) *L/K is unramified if and only if P_L does not divide $\mathfrak{D}$.*

2. Some preliminary results

We retain the notations of the preceding section. For α belonging to the algebraic closure $\tilde{K}$ of K, we shall write $\tilde{v}(\alpha)$ as $v(\alpha)$.

Lemma 2.1. *If $K \subseteq M \subseteq L$ is a tower of finite extensions of (K, v), then the following hold*:

(a) $\lambda_{L/M} + \lambda_{M/K} = \lambda_{L/K}$.
(b) *If L/K is a separable extension, then $C_{L/M}C_{M/K} \subseteq C_{L/K}$; further if $C_{M/K}$ is a principal ideal, then $C_{L/M}C_{M/K} = C_{L/K}$.*

Proof. Let l_0 and m_0 be elements of L and M, respectively, such that $v(l_0) = \lambda_{L/M}$ and $v(m_0) = \lambda_{M/K}$. First we show that

$$\lambda_{L/M} + \lambda_{M/K} \leqslant \lambda_{L/K}. \tag{3}$$

Suppose to the contrary that $\lambda_{L/K} < \lambda_{L/M} + \lambda_{M/K}$, so there exists $t \in K$ such that $0 < v(t) \leqslant v(l_0) + v(m_0)$, i.e., $v(t) - v(m_0) \leqslant v(l_0)$. As $v(m_0) = \lambda_{M/K}$, $v(t) - v(m_0)$ must be positive. Thus we see that t/m_0 is an element of M with positive valuation which is at most $\lambda_{L/M}$. This is impossible in view of the definition of $\lambda_{L/M}$. Hence (3) is proved.

To prove that equality holds in (3), let γ be any positive element of the value group G_M. By definition of $\lambda_{M/K}$, there exists $\delta \in G_K$ with $0 < \delta \leqslant \lambda_{M/K} + \gamma$. Since $\delta > \lambda_{L/K}$ by definition of $\lambda_{L/K}$, it follows that $\gamma > \lambda_{L/K} - \lambda_{M/K}$. This inequality holds for all $\gamma \in G_M$ with $\gamma > 0$, hence $\lambda_{L/M} \geqslant \lambda_{L/K} - \lambda_{M/K}$, which proves assertion (a) of the lemma.

To verify $C_{L/M}C_{M/K} \subseteq C_{L/K}$, note that for any α belonging to $C_{L/M}$ and a in $C_{M/K}$, we have $\mathrm{Tr}_{L/K}(a\alpha R_L) = \mathrm{Tr}_{M/K}(a\,\mathrm{Tr}_{L/M}(\alpha R_L)) \subseteq \mathrm{Tr}_{M/K}(aR_M) \subseteq R_K$ and hence the result. Suppose now that $C_{M/K}$ is a principal ideal generated by b. The chain of equivalences

$$\begin{aligned} \beta \in C_{L/K} \quad &\Leftrightarrow \quad \mathrm{Tr}_{L/K}(\beta R_L) \subseteq R_K \quad \Leftrightarrow \quad \mathrm{Tr}_{M/K}\bigl(\mathrm{Tr}_{L/M}(\beta R_L)R_M\bigr) \subseteq R_K \\ &\Leftrightarrow \quad \mathrm{Tr}_{L/M}(\beta R_L) \subseteq C_{M/K} = bR_M \quad \Leftrightarrow \quad b^{-1}\beta \in C_{L/M} \end{aligned}$$

proves that $C_{L/K} = C_{L/M}C_{M/K}$. $\square$

Lemma 2.2. *Let $K \subseteq M \subseteq L$ be a tower of finite separable defectless extensions of (K, v). If Theorem* 1.1 *holds for the extensions L/M and M/K, then it holds for L/K.*

Proof. By the hypothesis, $C_{L/M}$ and $C_{M/K}$ are principal ideals and

$$\min A_{L/M} = -\min_{\alpha \in C_{L/M}} \bigl\{v(\alpha)\bigr\} - \lambda_{L/M}, \qquad \min A_{M/K} = -\min_{\alpha \in C_{M/K}} \bigl\{v(\alpha)\bigr\} - \lambda_{M/K}.$$

Adding the above two equations and using (1) together with Lemma 2.1, we see that $C_{L/K} = C_{L/M}C_{M/K}$ and

$$\min A_{L/K} = -\min_{\alpha \in C_{L/M}} \bigl\{v(\alpha)\bigr\} - \min_{\alpha \in C_{M/K}} \bigl\{v(\alpha)\bigr\} - \lambda_{L/K} = -\min_{\alpha \in C_{L/K}} \bigl\{v(\alpha)\bigr\} - \lambda_{L/K}$$

as desired.

Lemma 2.3. *Let L be a finite defectless separable extension of (K, v). If $l' \in L$ is such that $v(\mathrm{Tr}_{L/K}(l')) - v(l') = \min A_{L/K}$, then $l'/\mathrm{Tr}_{L/K}(l')$ belongs to $C_{L/K}$.*

Proof. Let r be any element of R_L. For verifying that $\mathrm{Tr}_{L/K}(l'r/\mathrm{Tr}_{L/K}(l'))$ belongs to R_K, note that

$$\begin{aligned} &v\big(\mathrm{Tr}_{L/K}(l'r)\big) - v\big(\mathrm{Tr}_{L/K}(l')\big) \\ &\quad = v\big(\mathrm{Tr}_{L/K}(l'r)\big) - v(l'r) - \big[v\big(\mathrm{Tr}_{L/K}(l')\big) - v(l')\big] + v(r) \geqslant 0. \qquad \square \end{aligned}$$

Lemma 2.4. *Let $K \subseteq M \subseteq L$ be a tower of finite separable defectless extensions. If Theorem* 1.1 *holds for the extensions L/K and L/M, then it holds for M/K.*

Proof. By hypothesis, $C_{L/K}$ and $C_{L/M}$ are principal R_L-ideals generated by α_0 and α_1 respectively (say), and

$$\min A_{L/K} = -v(\alpha_0) - \lambda_{L/K}, \qquad \min A_{L/M} = -v(\alpha_1) - \lambda_{L/M}.$$

On subtracting and using formula (1) together with Lemma 2.1(a), it follows from the last two equations that

$$\min A_{M/K} = v(\alpha_1) - v(\alpha_0) - \lambda_{M/K}. \tag{4}$$

Claim is that $C_{M/K}$ is a principal ideal, i.e., the set $\{v(m) \mid m \in C_{M/K}\}$ has a minimum element which will indeed be equal to $v(\alpha_0) - v(\alpha_1)$ by virtue of Lemma 2.1(b). This will prove the lemma in view of (4). We now verify the claim. By Lemma 2.1(b) $C_{L/M}C_{M/K} \subseteq C_{L/K}$ and hence on recalling that $C_{L/K}, C_{L/M}$ are generated by α_0, α_1 respectively, we have $C_{M/K} \subseteq (\alpha_0/\alpha_1)R_L$, i.e.,

$$v(m) \geqslant v(\alpha_0) - v(\alpha_1) \quad \text{for all } m \in C_{M/K}.$$

The above inequality and (4) imply that for each m in $C_{M/K}$, one has

$$\min A_{M/K} + v(m) \geqslant -\lambda_{M/K}. \tag{5}$$

On setting $\min A_{M/K} = v(\mathrm{Tr}_{M/K}(m')) - v(m')$, $m' \in M$, inequality (5) can be rewritten as

$$v(m') - v\big(\mathrm{Tr}_{M/K}(m')\big) - v(m) \leqslant \lambda_{M/K}, \quad m \in C_{M/K}. \tag{6}$$

Keeping in mind that $\lambda_{M/K}$ is the maximum element of the finite set $S_{M/K}$ defined by (2) and that $m'/\mathrm{Tr}_{M/K}(m')$ belongs to $C_{M/K}$ by Lemma 2.3, it now follows from (6) that the set $\{v(m) \mid m \in C_{M/K}\}$ has minimum element $v(m') - v(\mathrm{Tr}_{M/K}(m')) - \lambda$ for some λ in $S_{M/K}$. This proves the claim and completes the proof of the lemma. $\square$

Definition. Let $(L, w)/(K, v)$ be an extension of degree n. A basis $\alpha_1, \ldots, \alpha_n$ of L/K is called a valuation basis (with respect to w/v) if for each $\alpha = \Sigma a_i\alpha_i$ in L, $a_i \in K$, the equation $w(\alpha) = \min_i w(a_i\alpha_i)$ holds.

Lemma 2.5. *Let $L = K(\theta)$ be a separable extension of degree n of (K, v) with $f(x)$ as the minimal polynomial of θ over K. The following hold*:

(a) *If $R_L = R_K[\theta]$, then $C_{L/K} = \frac{1}{f'(\theta)} R_L$.*
(b) *If $1, \theta, \ldots, \theta^{n-1}$ is a valuation basis of L/K (with respect to v), then*

$$\min A_{L/K} = v\big(f'(\theta)\big) - (n-1)v(\theta).$$

Proof. We prove only assertion (b) of the lemma as the first assertion is already known (see [7, Corollary 2, p. 56], [6, Theorem 4.6]). By hypothesis $1, \theta, \ldots, \theta^{n-1}$ is a valuation basis of L/K, hence so is $\frac{1}{f'(\theta)}, \frac{\theta}{f'(\theta)}, \ldots, \frac{\theta^{n-1}}{f'(\theta)}$. Let η be a non-zero element of L. Write $\eta = \sum a_i \theta^i / f'(\theta)$, $a_i \in K$. Then by what we have said above

$$v(\eta) = \min_i \left\{ v(a_i) + v\left(\frac{\theta^i}{f'(\theta)}\right)\right\}.$$

Also by the triangle law

$$v\big(\mathrm{Tr}_{L/K}(\eta)\big) \geqslant \min_i \left\{ v(a_i) + v\left(\mathrm{Tr}_{L/K}\left(\frac{\theta^i}{f'(\theta)}\right)\right)\right\}.$$

Therefore

$$v\big(\mathrm{Tr}_{L/K}(\eta)\big) - v(\eta) \geqslant \min_i \left\{ v\left(\mathrm{Tr}_{L/K}\left(\frac{\theta^i}{f'(\theta)}\right)\right) - v\left(\frac{\theta^i}{f'(\theta)}\right)\right\}. \tag{7}$$

By an elementary result of field theory (see [5, Chapter VI, Proposition 5.5], [7, Chapter 3, Lemma 2]), we have

$$\mathrm{Tr}_{L/K}\left(\frac{\theta^{n-1}}{f'(\theta)}\right) = 1, \qquad \mathrm{Tr}_{L/K}\left(\frac{\theta^i}{f'(\theta)}\right) = 0 \quad \text{for } 0 \leqslant i \leqslant n-2.$$

So the minimum on the right-hand side of (7) is $v(f'(\theta)) - (n-1)v(\theta)$. This proves the required result. □

Lemma 2.6. *Theorem* 1.1 *holds when L is any defectless separable extension of (K, v) of prime degree.*

Proof. Let q denote the degree of the extension L/K and $\bar{K} \subseteq \bar{L}$ stand for the residue fields as introduced in the first section. We split the proof into two cases:

Case I. $\bar{K} \neq \bar{L}$. Since L/K is defectless, there exists $\theta \in L$ such that $v(\theta) = 0$ and the v-residue of θ does not belong to the residue field of v. So the v-residue of θ is algebraic of degree q over the residue field $\bar{K}$ of v. Therefore for any element $\xi = \sum_{i=0}^{q-1} a_i \theta^i$ belonging to L, $v(\xi) = \min_i\{v(a_i)\}$, for otherwise $v(\xi) > \min_i\{v(a_i)\} = v(a_j)$ which would imply

$\sum_{i=0}^{q-1}(\overline{a_i/a_j})\bar{\theta}^i = \bar{0}$ and consequently $\bar{\theta}$ would satisfy a non-zero polynomial of degree less than q over $\bar{K}$, contrary to our assumption. Thus $1, \theta, \dots, \theta^{q-1}$ is a valuation basis of L/K and $R_L = R_K[\theta]$. On applying Lemma 2.5, we see that $C_{L/K}$ is a principal ideal and that the desired equality holds in the present case.

Case II. $G_L \neq G_K$. Let $S_{L/K}$ denote the set defined by (2). This case is split into two subcases.

Case II (a). $S_{L/K} \neq \{0\}$. Recall that $S_{L/K}$ is a finite set, we can chose $\theta \in L$ such that $v(\theta)$ is the least positive element of $S_{L/K}$. Now q (a prime number) is the least positive integer such that $qv(\theta) \in G_K$, so whenever a, b are any non-zero elements of K, then

$$v\big(a\theta^i\big) \neq v\big(b\theta^j\big), \quad 0 \leqslant i \neq j \leqslant q-1.$$

Therefore it follows from the strong triangle law that for any $\xi = \sum_{i=0}^{q-1} a_i\theta^i$ in L, we have $v(\xi) = \min_i v(a_i\theta^i)$; this proves that $1, \theta, \dots, \theta^{q-1}$ is a valuation basis of L/K. Keeping in mind that $(q-1)v(\theta)$ is the largest element of $S_{L/K}$, it can be easily checked that $R_L = R_K[\theta]$. Applying Lemma 2.5, we see that Theorem 1.1 holds in the present situation.

Case II (b). $S_{L/K} = \{0\}$. Let I be a well-ordered set such that $\{C_i,\ i \in I\}$ is the chain of all convex subgroups of G_L with $C_i \subset C_j$ for $i < j$. Let j be the least index such that $C_j \cap G_K \neq C_j$. Note that C_j/C_{j-1} is of rank one and hence is order isomorphic to a subgroup of the group $\mathbb{R}$ of real numbers under addition (cf. [10, p. 45]). Also $C_j/(C_j \cap G_K)$ being isomorphic to a non-trivial subgroup of G_L/G_K is of order q. Consequently $(C_j \cap G_K)/C_{j-1}$ is a subgroup of index q of C_j/C_{j-1}. Choose an element θ of L with $v(\theta) \in C_j \backslash (C_j \cap G_K)$ such that $v(\theta) + C_{j-1}$ is the least positive element of C_j/C_{j-1} in case C_j/C_{j-1} is a cyclic group. In case it is not cyclic, this group as well as $(C_j \cap G_K)/C_{j-1}$ will be order isomorphic to dense subgroups of $(\mathbb{R}, +)$ (cf. [1, 4.1]); consequently in this situation

$$v(\theta) = \sup\big\{v(a) \mid a \in K,\ v(a) \in C_j \cap G_K,\ v(a) < v(\theta)\big\}. \tag{8}$$

Keeping in mind that $v(\theta)$ belongs to $C_j \setminus (C_j \cap G_K)$ and arguing as in Case II(a), we see that $1, \theta, \dots, \theta^{q-1}$ is a valuation basis of L/K. In view of Lemma 2.5(b), the theorem is proved in the present situation, once we prove that

$$C_{L/K} = \frac{\theta^{q-1}}{f'(\theta)} R_L \tag{9}$$

where $f(x) = x^q - b_1x^{q-1} - \cdots - b_q$ is the minimal polynomial of θ over K. We first prove that

$$\frac{\theta^{q-1}}{f'(\theta)} R_L \subseteq C_{L/K}. \tag{10}$$

Let $\eta = \sum_{i=0}^{q-1} a_i\theta^i$, $a_i \in K$, be any element of R_L. It is required to be shown that

$$v\left(\mathrm{Tr}_{L/K}\left(\eta\frac{\theta^{q-1}}{f'(\theta)}\right)\right) \geqslant 0. \tag{11}$$

By an elementary result of field theory (see [5, Chapter VI, Proposition 5.5]), we have

$$\mathrm{Tr}_{L/K}\left(\frac{\theta^{q-1}}{f'(\theta)}\right) = 1, \qquad \mathrm{Tr}_{L/K}\left(\frac{\theta^{i}}{f'(\theta)}\right) = 0 \quad \text{for } 0 \leqslant i \leqslant q-2. \tag{12}$$

Using (12) repeatedly, a simple calculation shows that

$$\mathrm{Tr}_{L/K}\left(\eta\frac{\theta^{q-1}}{f'(\theta)}\right) = a_0 + a_1t_1 + \cdots + a_{q-1}t_{q-1}, \tag{13}$$

where

$$t_1 = b_1, \qquad t_i = b_1t_{i-1} + b_2t_{i-2} + \cdots + b_{i-1}t_1 + b_i, \quad 1 \leqslant i \leqslant q-1. \tag{14}$$

Recall that $\eta = \sum_{i=0}^{q-1} a_i\theta^i$ belongs to R_L and $1, \theta, \ldots, \theta^{q-1}$ is a valuation basis of L/K; consequently $v(a_i) + iv(\theta) \geqslant 0$ for $0 \leqslant i \leqslant q-1$. Therefore in view of (13), the desired inequality (11) is proved once it is shown that

$$v(t_i) \geqslant iv(\theta), \quad 1 \leqslant i \leqslant q-1. \tag{15}$$

We prove (15) by induction on i. As $f(x) = x^q - b_1x^{q-1} - \cdots - b_q$ is the minimal polynomial of θ over K, it follows that

$$v(b_i) \geqslant iv(\theta), \quad i \geqslant 1. \tag{16}$$

In particular $v(t_1) = v(b_1) \geqslant v(\theta)$ which gives (15) for $i = 1$. Assume that (15) holds for all i with $1 \leqslant i \leqslant k \leqslant q-2$. By virtue of (14), we have

$$v(t_{k+1}) \geqslant \min_{1 \leqslant i \leqslant k}\left\{v(b_it_{k+1-i}), v(b_{k+1})\right\}.$$

Now using induction hypothesis and (16), it follows that $v(t_{k+1}) \geqslant (k+1)v(\theta)$, which proves (15) for $i = k+1$. Thus the proof of (11) and hence that of (10) is complete.

For obtaining (9), it remains to be shown that

$$C_{L/K} \subseteq \frac{\theta^{q-1}}{f'(\theta)}R_L. \tag{17}$$

Take an element $\xi = \sum_{i=0}^{q-1} a_i\frac{\theta^i}{f'(\theta)}$ belonging to $C_{L/K}, a_i \in K$. To prove (17), it is required to be verified that $v(\xi f'(\theta)) \geqslant (q-1)v(\theta)$, which is the same as saying that

$$v(a_i) + iv(\theta) \geqslant (q-1)v(\theta), \quad 0 \leqslant i \leqslant q-1. \tag{18}$$

Recall that by the choice of θ, $v(\theta) + C_{j-1}$ is the least positive element of C_j/C_{j-1} in case C_j/C_{j-1} is a cyclic group and so $v(\theta)$ is the supremum of C_{j-1} in this case; also $v(\theta)$ satisfies (8) in the other case. Let a run over those elements of K for which $v(a) \in C_{j-1}$ when the group C_j/C_{j-1} is cyclic and $v(a) \in C_j \cap G_K$, $v(a) < v(\theta)$ in the other case. So (18) is proved once it is shown that for each such $v(a)$, we have

$$v(a_i) \geqslant (q-1-i)v(a), \quad 0 \leqslant i \leqslant q-1. \tag{19}$$

To verify the above inequality, let a be an element of K with $v(a)$ as above. Note that θ/a belongs to R_L. Keeping in mind that $\xi = \sum_{i=0}^{q-1} a_i \frac{\theta^i}{f'(\theta)}$ is an element of $C_{L/K}$, it follows that

$$\mathrm{Tr}_{L/K}\big(\xi(\theta/a)^k\big) \in R_K, \quad 0 \leqslant k \leqslant q-1. \tag{20}$$

Taking $k=0$ in (20) and using (12), we obtain $v(a_{q-1}) \geqslant 0$. Again using (20) for $k=1$ and (12), it can be easily seen that $v(a_{q-2} + a_{q-1}b_1) \geqslant v(a)$, which together with the fact $v(a_{q-1}) \geqslant 0$ and $v(b_1) \geqslant v(\theta) > v(a)$ implies that $v(a_{q-2}) \geqslant v(a)$. Thus (19) is verified for $i = q-1, q-2$. Now using (20) for $k=2$ and arguing as above, we shall obtain $v(a_{q-3}) \geqslant 2v(a)$. Proceeding like this, (19) and hence (18) is proved. This proves (17) and completes the proof of (9). □

Lemma 2.7. *Theorem* 1.1 *holds if we have the extra hypothesis that the extension L/K is unramified.*

Proof. As L/K is unramified, $\bar{L}/\bar{K}$ is a separable extension of degree $[L:K]=n$. So there exists an element θ in L such that $v(\theta)=0$ and $\bar{L} = \bar{K}(\bar{\theta})$. Proceeding as in the proof of Case I of Lemma 2.6, it can be easily seen that $1, \theta, \ldots, \theta^{n-1}$ is a valuation basis of L/K, $R_L = R_K[\theta]$ and the desired assertion follows from Lemma 2.5. □

Lemma 2.8. *Let N be a finite Galois extension of K. Then Theorem* 1.1 *holds for the maximal tame extension of* (K, v) *contained in N.*

Proof. Let K^T, K^V be the inertia field and ramification field of N/K (with respect to v). By ramification theory, K^V is the maximal tame extension of (K, v) contained in N, K^T/K is an unramified extension and K^V/K^T is an abelian extension.

So there exists a tower of field extensions

$$K^T \subset K_1 \subset \cdots \subset K_s = K^V$$

such that each extension K_i/K_{i-1} is of prime degree. The lemma now follows immediately from Lemmas 2.2, 2.6 and 2.7. □

3. Proof of Theorem 1.1

Let $p \geqslant 0$ denote the characteristic of the residue field of v. Let N be a finite Galois extension of K containing L and K^V be the ramification field of N/K with respect to v. Then N/K^V is a p-extension if $p > 0$ and $N = K^V$, otherwise. Since tameness is preserved under composition [1, 20.15], LK^V/L is a tame and hence defectless extension. Therefore LK^V/K is a defectless extension. In view of Lemma 2.4, Theorem 1.1 is proved for the extension L/K as soon as it is shown that it holds for the defectless extensions LK^V/K and LK^V/L.

We first verify the validity of the theorem for LK^V/K. Consider the groups

$$H_0 = \mathrm{Gal}\big(N/K^V\big), \quad H = \mathrm{Gal}\big(N/LK^V\big).$$

Since H_0 is a p-group, there exists a descending chain of subgroups

$$H_0 \supset H_1 \supset \cdots \supset H_t = H \supset H_{t+1} \supset \cdots \supset \{e\}$$

such that each H_i is normal subgroup of H_{i-1} of index p. If K_i denotes the fixed field of H_i, then

$$K^V = K_0 \subset K_1 \subset \cdots \subset K_t = LK^V$$

is a tower of extensions of degree p each. By Lemma 2.6, Theorem 1.1 holds for K_i/K_{i-1}, $1 \leqslant i \leqslant t$, and consequently for LK^V/K^V in view of Lemma 2.2. It is valid for K^V/K by Lemma 2.8 and thus is valid for LK^V/K.

It only remains to show that the theorem holds for LK^V/L. Let M be the maximal tame extension of L contained in N. As LK^V/L is tame, M contains LK^V. By Lemma 2.8, the theorem holds for M/L. So in view of Lemma 2.4, it is enough to verify the validity of the theorem for M/LK^V. Since N/LK^V is a Galois p-extension with subextension M/LK^V, arguing as in the above paragraph and applying Lemmas 2.6, 2.2, it can be seen that the theorem holds for the extension M/LK^V. This completes the proof.

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